Extended Abstract

Synthesis of Bio- Based Phase Change Materials Enhanced with Natural Wax, Metal oxide Nano additive, and Porus Carbon for Thermal Energy Storage

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Scope of the Thesis

The increasing demand for sustainable energy technologies and the need to enhance the utilization of renewable energy resources remain critical challenges for achieving energy security and environmental sustainability. In this context, thermal energy storage systems play a vital role in improving the efficiency and reliability of solar energy applications. Among available technologies, latent heat thermal energy storage using phase change materials (PCMs) has emerged as a promising approach due to its high energy storage density and ability to maintain nearly constant temperature during phase transitions. However, conventional organic PCMs, particularly fatty acids, exhibit low thermal conductivity due to limited phonon transport and may experience structural instability during phase transition, affecting thermal transport efficiency in solar thermal systems.

The scope of this thesis is to develop bio-based composite PCM systems through a systematic material design strategy aimed at addressing the limitations associated with conventional organic PCMs. Fatty acids are utilized as base PCMs, while natural waxes are incorporated to improve structural stability and modify phase transition behaviour. The incorporation of natural wax into fatty-acid-based eutectic systems induces a slight shift in melting temperature and broadens the phase change range. Although the distinct eutectic melting peak becomes less pronounced, this modification can enhances form stability, reduces leakage, and improves the practical applicability of the PCM for solar thermal energy storage. Furthermore, the incorporation of metal oxide (TiO_2) nano additives is explored to enhance thermal transport properties by introducing additional conductive pathways within the PCM matrix. The presence of these nanoparticles improves heat transfer by facilitating energy transport between the PCM and dispersed particles, as well as between neighbouring nanoparticles. These nanoparticles also act as heterogeneous nucleation sites, facilitating more uniform crystallization and helping to reduce supercooling effects. Porous carbon materials such as expanded graphite (EG) and EG-derived carbon matrix provide a dual function by forming interconnected, percolative thermally conductive networks that significantly enhance heat transport within the PCM system. These continuous pathways enable efficient heat flow across the material, significantly reducing thermal resistance compared to nanoparticle-based systems. At the same time, their porous structure enables capillary-driven confinement of the liquid phase, thereby improving shape stability and reducing leakage during phase transition.

In addition to material development, the thesis integrates experimental investigations with numerical simulations to evaluate the thermal performance of the developed PCM systems under realistic solar thermal conditions. This combined approach provides deeper insights into heat transfer mechanisms, phase transition behaviour, and system-level performance.

Questions addressed in this thesis are:

- How can eutectic composition of fatty-acid-based PCMs be optimized to achieve desired phase transition temperatures for solar thermal applications?
- What role do natural waxes play in improving structural stability and mitigating leakage during phase transition?
- How does metal oxide nanoadditives influence thermal conductivity and crystallization behaviour in composite PCM systems?
- How can porous carbon materials enhance shape stability and heat transfer performance of PCMs?
- How do these material modifications affect the overall thermal response and efficiency of PCM-based solar thermal systems?

Thesis is Structured as Follows :

Chapter 1: Introduction

This chapter presents an overview of thermal energy storage systems and phase change materials (PCMs) as key technologies for improving the efficiency of renewable energy systems. It discusses the fundamentals of latent heat storage, the classification and properties of PCMs, and the limitations associated with conventional organic PCMs. The need for developing advanced bio-based composite PCM systems is established, and the motivation for integrating natural waxes, nanoadditives, and porous carbon materials is outlined.

Chapter 2: Fundamentals and Literature Review

This chapter provides a comprehensive review of the fundamental principles governing phase change materials, including thermodynamics of phase transitions and heat transfer mechanisms in latent heat storage systems. It surveys recent advancements in fatty-acid-based PCMs, natural wax-modified systems, nano-enhanced PCMs, and porous carbon-stabilized composites. Existing challenges and research gaps in improving thermal conductivity, stability, and applicability of PCMs are identified to define the direction of the present study.

Chapter 3: Experimental Methods and Characterization Techniques

This chapter describes the materials, synthesis procedures, and methodologies used for the development of PCM systems. It includes the preparation of binary eutectic PCMs, nano-enhanced composites, and carbon matrix stabilized PCM systems. The synthesis of porous carbon from expanded graphite via solvothermal processing is presented. The chapter also outlines the techniques used to evaluate thermophysical, structural, and chemical properties, along with the numerical simulation methodology employed to analyse heat transfer behaviour of PCM systems.

Chapter 4: Development of Beeswax-Based Binary Eutectic PCM and TiO_2 Nano-Enhanced Composite Systems

This chapter focuses on the design and development of beeswax-based binary eutectic PCM systems using fatty acids such as lauric, myristic, palmitic, and stearic acids. The influence of eutectic composition on phase transition temperature and latent heat storage is investigated. Additionally, nano-enhanced PCM systems are developed by incorporating TiO_2 nanoparticles into stearic acid–beeswax composites, and their impact on thermal transport properties, crystallization behaviours, and thermal stability is analysed.

Chapter 5: Myricyl Cerotate-Rich Natural Wax and Porous Carbon Reinforced PCM for Thermal Energy Storage

This chapter explores advanced composite PCM systems reinforced with myricyl cerotate-rich Carnauba wax and porous carbon materials. The synergistic effects of Carnauba wax and porous carbon on phase transition characteristics, thermal stability, and heat transfer performance are investigated. The potential of these composites for efficient thermal energy storage applications is analysed.

Chapter 6: Carbon Matrix Stabilized Fatty-Acid-Based PCM

This chapter presents the development of shape-stabilized PCM systems using a porous carbon matrix synthesized from expanded graphite via a solvothermal process. The role of the carbon matrix in preventing leakage, improving structural stability, and enhancing heat transfer performance is examined. The thermal behaviours of the developed composites is further evaluated, along with their performance under simulated thermal energy storage conditions.

Chapter 7: Conclusions and Future Scope

This chapter summarizes the major findings of the thesis and highlights the significance of bio-based composite PCM systems in improving solar thermal energy storage technologies. Future research directions include optimization of material composition, development of advanced nano additives and porous structures, and large-scale implementation of PCM systems in renewable energy applications.